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A Novel Tone Mapping Method for High Dynamic Range Image by Incorporating Edge-Preserving Filter Into Method Based on Retinex

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Abstract: A tone mapping method for high dynamic range image is proposed to prevent the halo artifacts, which is easy to be produced in traditional method based on the Retinex theory in handling high dynamic range(HDR) image. Our method is based on the Retinex theory. The novelties of our method is first to employ a local edge-preserving filter for the estimation of the illumination, which can smooth out the small-scale details while the large-scale edges are retained. Second, the filter is incorporated into the method based on MSR algorithm, in which the Gaussian filter is replaced by this filter in order to prevent the halo artifacts and a multi-scale operation is applied for preserving more details. Finally, a post-processing step is adopted to compress the dynamic range and prevent the underexposure or overexposure. We tested our method on a variety of HDR images and compared it with other typical methods. The experimental results show that the proposed method can not only prevent the halo artifacts, but also can get higher contrast and more clearly details.

Keywords: High Dynamic Range, Tone Mapping, Edge-Preserving Filter, Retinex, Color Restoration.

1 Introduction

High dynamic range (HDR) image has been widely used in areas of digital film, television, play games, military, astronomy and medicine, this is because of its ability of reproducing luminance values in a range of $0.001cd/m^2$ to $100000cd/m^2$. The dynamic rang is defined as the ratio between the highest and the lowest luminance level of the scene [1]. Although the dynamic range of a HDR image can span over ten orders of magnitude, but most current hardcopy and display devices, such as CRT monitors and printers, can approximately reproduce two or three orders of magnitude. So a compression of the dynamic range for rendering HDR images on low dynamic rang(LDR) devices is required, this is commonly called tone mapping [2].

In past decades, there is a great deal of work in the literate on tone mapping techniques. According to the mapping function, they can be classified into global and local technique. Global tone mapping methods compress the dynamic range of a HDR image using the same mapping function for all pixels, such as gamma function, logarithm function, sigmoidal function and so on. The advantage of the global mapping method is that it is simple and fast. However, it can cause contrast reduction and thus a loss of details of the processed image. In contrast, the mapping function in local operators is changed according to the neighborhood of a pixel. Local processing can increase the local contrast, and preserve more details of the image, so most existing works in recent years devote more attention to the local tone mapping method [3,4] .

The main idea of local tone mapping method is to firstly decompose an image into a base layer and a detail layer. The base layer containing large scale variation in intensity bears high dynamic range, while the range of the detail layer is low. Then the base layer is compressed by a non-linear mapping function. Finally, it is recombined with the detail layer. The most critical step in the local tone mapping method is the filter used in the decomposition process for the estimation of the illumination component, and different approaches have been proposed in the literature. The methods based on low pass filters, such as Gaussian filter, can cause significant halo artifacts near edges in the result image.

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The presence of halo artifacts is a well-known issue in local tone mapping methods. A common solution to this problem is to use edge-preserving filter which can smooth out the small scale details while preserving the large scale edges. Several edge-preserving filters have been proposed in the literature, such as anisotropic diffusion [5], weight least squares [6], bilateral filter[3]and so on. Among these, the best one is the bilateral filter(BLF) proposed in reference [3]. BLF is a non-linear edge-preserving filter with the weights depended by the spatial distance and the pixel value difference of its neighbors. It is quite effective in noise removal, but in the aspect of edge preserving, its ability is rather limited. When the scale of the extracted details increases, the BLF tends to blur over more edges, which may produce halo artifacts [7]. In this paper, an edge-preserving filter, called WLSF proposed by Farbman et al. [7], is employed for extraction of multi-scale details. The WLSF is an edge-preserving smoothing operator based on the weighted least squares, which can not only smooth oscillating details, but also preserve salient edges, it is much better than BLF.

Our method belongs to the category of methods based on the Retinex theory and is specifically designed in order to prevent the halo artifacts. The novelty of our method is first to use WLSF for the estimation of the illuminate component at three scales, which can preserve the high-contrast edge, thus reducing halo artifacts. Second, the fusion of the WLSF and the Retinex method was specifically designed. Third, an adaptive function is adopted so as to compress the dynamic range, and then the image colors are recovered by using exponential function. We compare our method with the other typical methods, the experimental results show that our method can efficiently render HDR images.

The rest of this paper is organized as follows. In Section 2, we briefly introduce the method based on Retinex theory. In Section 3, we describe in detail the method we proposed in this paper. The experiments are discussed in Section 4. Following that, the conclusion is given in Section 5.

2 The tone mapping method based on Retinex theory

2.1 Retinex theory

The Retinex theory was initially proposed by Land et al[8]. The main idea of this theory is to decompose an image into an illumination image and reflectance image by exploiting the characteristics of human vision. The illumination image is mainly formed by the light sources in the scene, and varies slowly. The reflectance image corresponds to the details of the object in the scene. The primary goal of his theory is to compress the illumination components while the reflectance components are retained. This theory is widely used in enhancing images at early stage. Now, it is a valuable method in compressing the dynamic range of a HDR image [2,9].

Based on the Retinex theory, different kinds of image enhancement algorithms have been proposed. The most applied algorithm is centre/surround retinex algorithm. Two typical versions of this algorithm are the signal-scale retinex(SSR) algorithm [10] and the multi-scale retinex(MSR) algorithm [11].

The SSR algorithm was proposed by Jobson et al. in reference [10], it can be expressed as:

$$R(x,y) = log(I(x,y)) - log(F(x,y) \otimes I(x,y)) \quad (1)$$

Where $R(x,y)$ represents the reflection component image,$I(x,y)$ is the input image, $\otimes$ denotes the convolution operation,and $F(x,y)$ is the surrounding function as follows:

$$F(x,y) = Aexp(-(x^2+y^2)/\sigma^2) \quad (2)$$

Where σ is the scale, and A is a constant, whose value must satisfy the condition of $\int\int F(x,y)dxdy = 1$

The MSR is an expand version of the SSR that aims to reduce halo artifacts caused by the SSR. The MSR is described in (3):

$$R(x,y) = \sum_{k=1}^{K} \omega_k (log(I(x,y) - log(F_k(x,y) \otimes I(x,y)) \quad (3)$$

Where K is the number of scales, $F_k(x,y)$ represents a surround function in different scales, ω_k is the weight value under different scales and $\sum_{k=1}^{K} \omega_k = 1$.

2.2 The tone-mapping method based on the Retinex theory

The tone-mapping methods based on the Retinex theory attempt to decompose an image into the illumination and reflectance components and process them separately. The illumination components are firstly compressed with a suitable nonlinear function in order to reduce its dynamic range, and then the two components are recombined to produce the output image. The main steps of this kind of algorithm are as following:

(1) Calculate the brightness of the image

$$I_{in} = 0.299R + 0.587G + 0.114B \quad (4)$$

(2) Compress the dynamic rang using MSR

$$L_1 = \sum_{k=1}^{K} \omega_k (log(I_{in}(x,y) - log(F_k(x,y) \otimes I_{in}(x,y))) \quad (5)$$

(3) Exponential transform and normalization

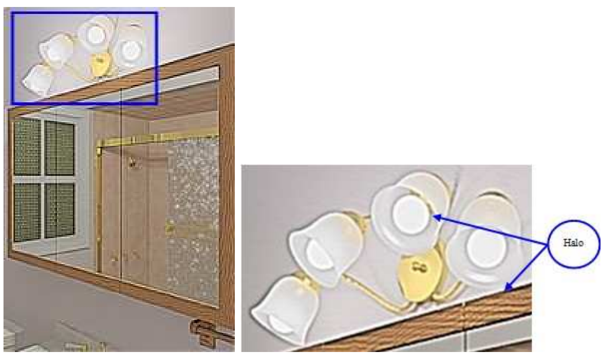
$$L_2 = exp(L_1) \quad (6)$$

$$I_{out} = \frac{L_2 - min(L_2)}{max(L_2) - min(L_2)} \tag{7}$$

(4) Color restoration

$$\begin{cases} R_{out} = (\frac{R}{I_{in}})^s \times I_{out} \\ G_{out} = (\frac{G}{I_{in}})^s \times I_{out} \\ B_{out} = (\frac{B}{I_{in}})^s \times I_{out} \end{cases} \tag{8}$$

Fig.1 shows a reproduced HDR image obtained by the method based on MSR. The enlarged detail of the blue rectangle in Fig.1(a) is given in Fig.1(b). We can find the halo artifacts at the edges of the lamp and the mahogany from Fig. 1(b).



(a) (b)

Fig. 1: Example of the reproduced HDR image obtained by the method based on MSR.(a) Method based on MSR; (b) The enlargement of the blue areas in Fig. 1(a).

A common drawback of the local tone mapping method based on Retinex is the presence of halo artifancts at the edges of two areas with different intensity. The reason is its assumption that the illumination is spatially smooth, and thus the high-frequency components are filtered out by the low-pass filter, which leads to halo artifacts in the presence of high-contrast edges. The traditional local tone mapping method based on Retinex use a Gaussian filter to estimate the illumination components, which will produce significant halo artifacts in result image. In order to overcome this problem, much effort is devoted to design new filter to replace the Gauss filter. One well-known example is the bilateral filter [3], it is employed to estimate the illumination component and achieves much better results. However, it is hard to determine the parameters of the bilateral filter. Recently, an edge-preserving filter, namely WLSF, was proposed by Farbman et al. Thanks to the ability of its edge-preserving at different scales, we employ it for the estimation of the illumination component.

3 The proposed method

A block diagram of the proposed method is shown in Fig. 2. The most critical part in Fig. 2 is the choice of the filter for estimating the illumination component. The novelty of our method use WLSF for the estimation of illumination component and we incorporate it into the method based on MSR algorithm. In the following sections, we will describe the proposed method in details.

3.1 The illumination estimation using WLSF filter

WLSF filter was proposed by Farbman et al in reference [7] in 2008. It belongs to the kind of edge-preserving filters. The main idea of the tone mapping algorithm using edge-preserving filter decompose an image into a base layer and a detail layer, the base layer is compressed with an appropriate method and then recombined with the detail layer.

WLSF is an edge-preserving smoothing filter based on the framework of weighted least squares. Unlike the bilateral filter, this filter can get the base layer at different scales, which the small-scale details are smoothed but the large-scale edges are retained. And more importantly, it looks like the original image [4].

The basic idea of the WLSF is to obtain a new image, which is as close as the original image and smooth as possible at everywhere except the areas with the salient gradients. It can be expressed as the minimum of the energy function as follows [7]:

$$E = \sum_p ((u_p - g_p)^2) + \lambda (a_{x,p}(g)(\frac{\partial u}{\partial x})_p^2 + a_{y,p}(g)(\frac{\partial u}{\partial x})_p^2)) \tag{9}$$

where g is a given input image,u is a new image we want to obtain. The subscript p denotes the spatial position of a pixel. The goal of the first term $(u_p - g_p)^2$ is to ensure image u and g as similar as possible, while the second term is the smooth item by minimizing the partial derivatives of $(\frac{\partial u}{\partial x})_p$ and $(\frac{\partial u}{\partial y})_p$ to ensure the smoothness of the image u. The smoothness requirement is ensured by the smoothness weights $a_{x,p}(g)$ and $a_{y,p}(g)$ which vary according to the spatial position on the image g:

$$\begin{cases} a_{x,p}(g) = (|\frac{\partial l}{\partial x}(p)|^\alpha + \varepsilon)^{-1} \\ a_{y,p}(g) = (|\frac{\partial l}{\partial y}(p)|^\alpha + \varepsilon)^{-1} \end{cases} \tag{10}$$

where the parameter α is used to control the sensitivity to the gradients of g,usually ranging from 1.0 to 1.8.l is the log-luminance of the input image g,that is $l = log(g + 0.000001)$,ε is a constant for preventing division zero in areas where g is constant, here we set $\varepsilon = 0.00001$.

The parameter λ in equation (9) is introduced to achieve the edge-preserving effect, which is used to balance between the first term and the second term. It should be large in the smooth portion of the image and small near the high-contrast edges. In this paper, λ is regarded as the scale parameter and we obtain the base layer images at three different scales, containing the details at different scales.

3.2 Dynamic range compression

The Gaussian filter is used to estimate the illumination component in the method based on the Retinex theory. Although it has a good smoothing effect, but does not have the role of the edge-preserving. In this paper, the WLSF is used to replace the Gauss filter in order to prevent the formation of the halo artifacts. The WLSF is incorporated into the MSR algorithm as follows:

$$R(x,y) = \sum_{k=1}^{K} \omega_k (logI(x,y) - L_k(x,y)) \tag{11}$$

$$L_k(x,y) = WLSF(logI(x,y), \lambda_k) \tag{12}$$

where $WLSF(\bullet)$ is an operator that the WLSF is used to the log-luminance of the input image $I(x,y)$ at the scale λ_k . In the equation (11), the illuminant effect is completely removed, this leads to the image dynamic range is too narrow, and the image looks unnatural. So it improved as follows:

$$R(x,y) = \sum_{k=1}^{K} \omega_k (logI(x,y) - \varphi_k L_k(x,y)) \tag{13}$$

where φ_k (typically between 0.8 and 1.0) is used to determine the removal degree of the illuminant.

The reflectance $R(x,y)$, after processed by the MSR and WLSF, is further processed by a post-processing step as shown in Fig. 2. The exponential transform is firstly applied to the reflectance $R(x,y)$, and then 1% of pixels are cut at low and high values considering noise and increasing the major pixels contrasts[4]. Lastly, the range is stretched linearly to [0, 1]. The above operations can be expressed by equation (14) and (15):

$$R_1(x,y) = exp(R(x,y)) \tag{14}$$

$$R_2(x,y) = \begin{cases} 0, & R_1(x,y) < T_l \\ \frac{R_1(x,y) - T_l}{T_h - T_l}, & T_l \le R_1(x,y) \le T_h \\ 1, & R_1(x,y) > T_h \end{cases} \tag{15}$$

where T_l is the low value corresponding to the value at the position of 1% of pixels in the histogram of the image $R_1(x,y)$, while T_h is the high value corresponding to the value at the position of 99% of pixels in the histogram of the image $R_1(x,y)$.

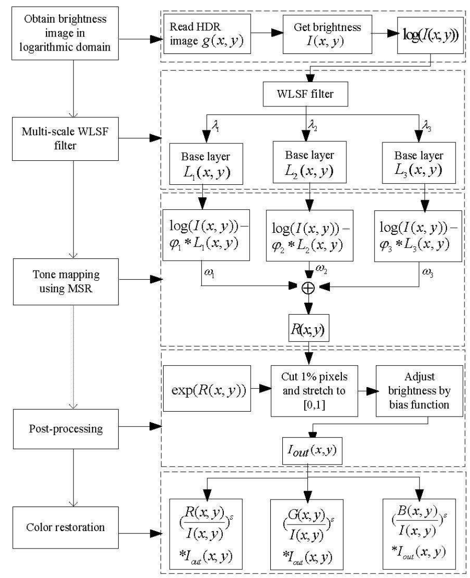


Fig. 2: Framework diagram of the proposed method

In order to further improve the brightness of the image, an adaptive adjustment function introduced by Drago et al.[12], which is adopted to adjust the image bright and the gray scale is changed to the range [0,255]. The function is:

$$I_{out} = (R_2(x,y)^{\frac{log(b)}{log(0.5)}}) \times 255 \tag{16}$$

Where b is the adjustment parameter, its range is [0.5, 1.0]. By adjusting its value, we can achieve image with different shades. We set $b = 0.78$ by the experiment.

3.3 Color restoration

All the above processes are done on the luminance channel of an HDR image. We restore the color information using equation (8) introduced in [13]. The exponent in equation(8) is used to control color saturation of the result image. We set $s = \frac{1}{2.2}$ in this study determined by experiment.

4 Experimental results

We test our method on various HDR images, and compared it with other typical methods. In the experiment, we use WLSF in three scales for the estimation of illumination, and the corresponding scale values are $\lambda_1 = 1, \lambda_2 = 5$, and $\lambda_3 = 25$. The parameter values used in (12) for MSR algorithm are $\omega_1 = 0.25, \omega_2 = 0.5$, $\omega_3 = 0.25, \varphi_1 = 0.85$, $\varphi_2 = 0.85$, and $\varphi_3 = 0.85$. All the above parameters are determined by the experiments, which achieve good results for most images. In the following section, we compare the results obtained by ours and others methods in details.

4.1 The comparison between the proposed method and the method based on MSR

In order to test the effect of reducing the halo artifacts, we first compare our method with the method based on MSR. Fig. 3 shows the rendering results of an HDR image, which is named bathroom with the dynamic range of 56280:1. The enlarged details of the blue rectangle areas in Fig.3(a) and Fig.3(b) are shown in the top and the bottom of Fig.3(c) respectively. We can observe that the halo artifacts in the bottom of Fig.3(c) depicted by arrows are reduced by our method.

(a) (b) (c)

Fig. 3: Comparison of a reproduced HDR image between ours and the method based on MSR.(a)our method;(b)method based on MSR;(c)the enlarged details of (a) and (b).

(a) (b) (c)

Fig. 4: Comparison of another HDR image between ours and the method based on MSR.(a)our method;(b)method based on MSR;(c)the enlarged details of (a) and (b).

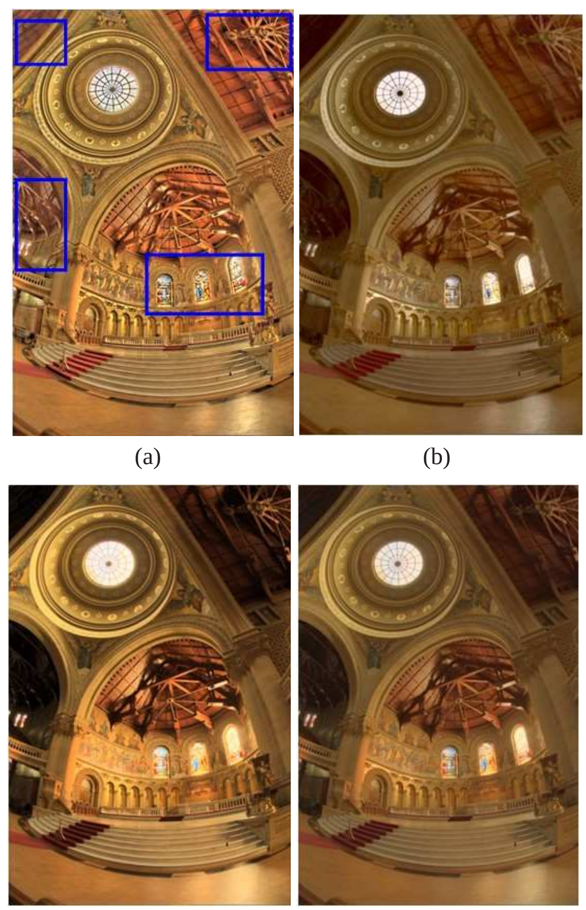
Fig. 4 gives the rendering results of another HDR image, which is named clockbui with the dynamic range of 12869:1, and the enlarged details of the blue rectangle areas in Fig. 4(a) and Fig. 4(b). We can also find the halo artifacts at the bottom of Fig.4 (c) produced by the method based on MSR are removed by our method. Moreover, one can discern more details in Fig. 4 (a), especially the clouds in the sky, while Fig. 4(b) lost the details.

From Fig. 3 and Fig. 4, we can see the method proposed in this paper not only avoid the phenomenon of the "Halo" , but also retain more details than the method based on MSR.

4.2 The comparison between our method and other typical methods

We also take our experiment on various HDR images. Fig. 5 gives the results on the famous memorial church image in comparisons with other seven methods in [2,3,7, 12,13,14,15]. When we examine the image contrasts and details, one can pay more attention to the four areas depicted in Fig.5(a) by blue rectangle. In order to carefully contrast the details reproduced by different methods, the enlarged details of the area with three arched windows in Fig. 5(a) are shown in Fig. 6.

From Fig. 5 and Fig. 6, we can make the following observations:



(a) (b)

(c) (d)

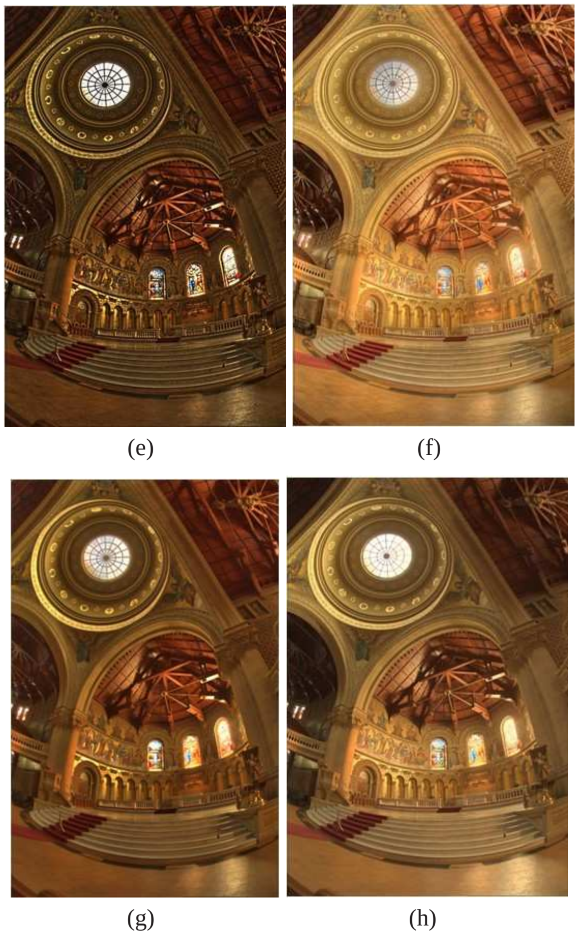


Fig. 5: Comparison of the reproduced memorial church image.(a)our method;(b)method of [2];c)method of [3];(d) method of [7];(e)method of [12];(f) method of [13];(g)method of [14];(h)method of [15].

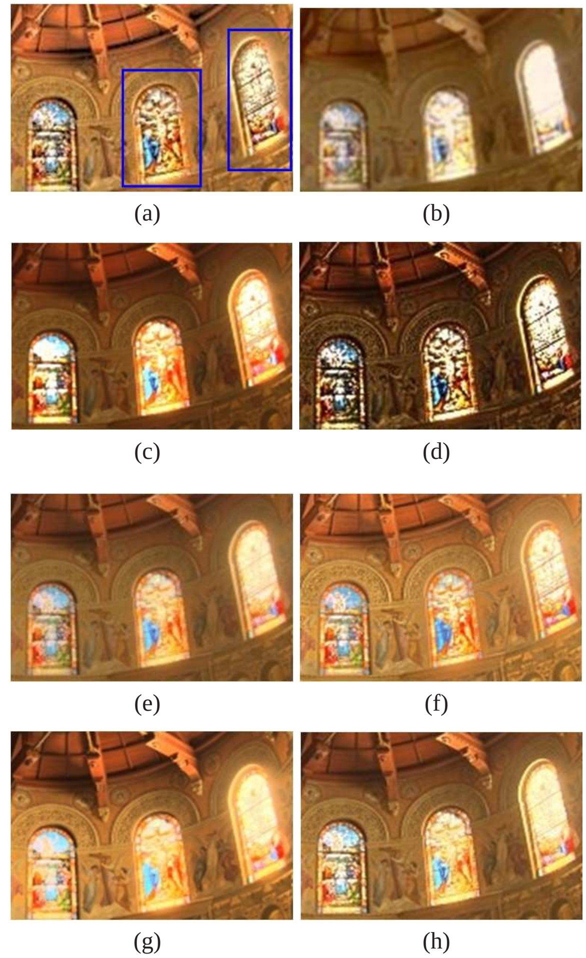


Fig. 6: Comparisons of enlarged details in Fig. 5 with different typical methods.(a)our method;(b)method of [2];c)method of [3];(d) method of [7];(e)method of [12];(f) method of [13];(g)method of [14];(h)method of [15].

(1) Our method achieves better contrast than the others. The image obtain by our method in Fig.5(a) looks more natural and clearer globally than others, while other methods still stuffer from drawbacks. For example, there exist overexposures in the third arched window of Fig.5(b) and the circular skylight of Fig.5(g), and underexposures in the upper left of Fig.5(e), Fig.5(g) and Fig.5(h). Although there are more details in Fig.5(c) and Fig.5(d), but the image looks dark on brightness and color in whole. The image of Fig.5(f) has low contrast compared with our method.

(2) Our result preserves more details than other methods. We can discern more details in Fig.6(a),which the sculpture of human in the three arched windows are especially clear than the others. The results of Fig.6(b), Fig.6(e) and Fig.6(h) show little details compare with our method.

5 Conclusion

A novel tone mapping method is proposed to overcome the problem of halo phenomenon which is easy to be produced in traditional method based on the Retinex theory. The proposed method is compared with other typical methods. The comparisons show that our method achieves a good rendition for HDR images, which can preserve more details while preventing the halo artifacts.The authors are grateful to the anonymous referee for a careful checking of the details and helpful comments that improved this paper.

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